PROJECT

2

CCD PHOTOMETRY

Objective: The objective of this project is the determination of astronomical magnitudes of point sources through the use of CCDs and aperture photometry. The process of transformation to a standard system is also described in detail.

Observations:
- a set of bias frames at the beginning and at the end of the night
- a set of flat-field images for each filter, B and V
- a set of CCD images of a couple of standard fields measured at various (at least 4) different values of the airmass
- a CCD image of a target star (it can be one of the standard stars) taken through the B and V filters. This exercise requires the acquisition of two images, in B and V filters, of an open cluster

Theory topics: Absolute and instrumental magnitudes, colour of a star, atmospheric extinction, transformation equations, standard system.

Analysis: Calibration of CCD images, obtain instrumental magnitudes, calculate atmospheric extinction, obtain magnitudes outside atmosphere, transform to the standard system.

Contents: CCD Photometry

Preliminary remarks

The main objective of this project is to obtain the apparent B and V magnitude of a target star. Standard fields can be found in, for example, Landolt (1992, AJ, 104, 340). Paul S. Smith of the NOAO/Kitt Peak National Observatory has a nice web site with all the required information including finding charts.

http://www.noao.edu/wiyn/queue/images/atlasinfo.html

Also, f*or the preparation of this project the Image Reduction and Analysis Facility (IRAF) has been employed. This is a general purpose software system for the reduction and analysis of astronomical data which is freely available on http://iraf.noao.edu/*

IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.

We also recommend the astronomical imaging and data visualization application SAOImage DS9 (http://hea-www.harvard.edu/RD/ds9/)

CCD Photometry

1. Absolute and apparent magnitudes

The **apparent magnitude** (***m***) of a star is a measure of its apparent brightness as seen by an observer on Earth. The brighter the object appears, the lower the numerical value of its magnitude.

The absolute magnitude ***(M)*** of a star is the apparent magnitude it would have if it were 10 parsecs (~ 32 light years) away.

The apparent and absolute magnitudes are related by means of the **distance-modulus** equation

$$m-M=-5+5\log_{10}(d)$$

where d is the distance to the star in parsecs. m-M is called the distance-modulus.

Exercise 1: The two Magellanic Clouds are irregular dwarf galaxies orbiting our Milky Way galaxy, and thus are members of our Local Group of galaxies. They are visible with naked-eye in the southern skies. The Large Magellanic Cloud (LMC) is rich in gas and dust, and it is currently undergoing vigorous star formation activity. The distance-modulus of the LMC and the SMC are 18.56±0.02 and 19.05 ±0.02, respectively. Calculate the distance of these two clouds.

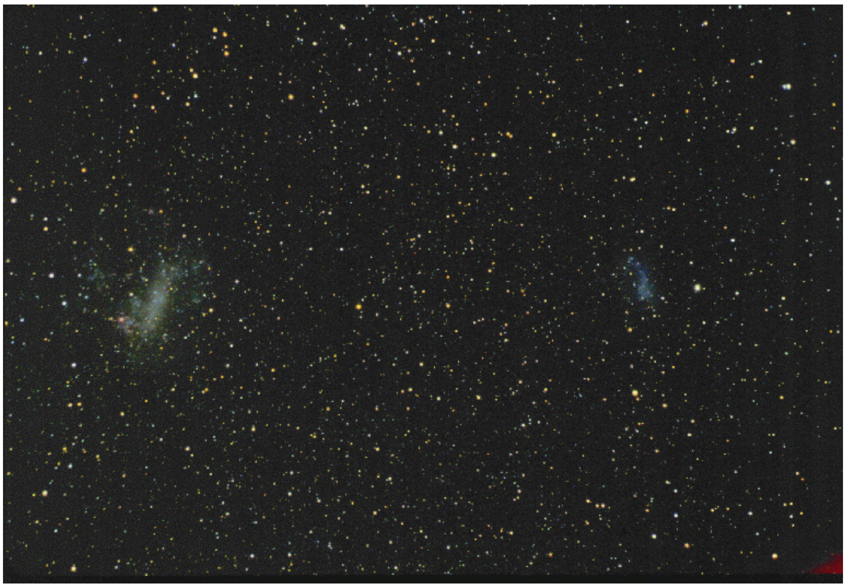


Fig. 1. The Magellanic Clouds

2. Pogson's scale

In 120 B.C. Hipparcus classified the naked-eye stars according to their brightness into six categories or magnitudes. The brightest stars were assigned to category one (first magnitude) and the faintest stars to category six (sixth magnitude), which is the limit of human visual perception (without the aid of a telescope). In between the brightest and the faintest stars were stars of second magnitude, third magnitude and so on. In 1856, Pogson formalized the system by defining a typical first magnitude star as a star that is 100 times as bright as a typical sixth magnitude star; thus, a first magnitude star is about 2.512 times as bright as a second magnitude star. This means that the system of magnitudes is logarithmic, with a base of 2.512 rather than the more familiar 10.

In magnitude, higher numbers correspond to fainter objects, lower numbers to brighter objects; the very brightest objects have negative magnitudes.

Exercise 2: Knowing that the difference of 1 magnitude corresponds to a factor of 2.512 in brightness, complete the following table.

Δm	**Factor in brightness**
1	2.512
2	
3	16
4	
5	100
6	
7	
8	
9	
10	

In other words a first magnitude star is 100 times as bright as a typical sixth magnitude star (Δm=5).

3. The colour of a star

Rather than just have one apparent magnitude, measured across the entire visible spectrum we can use a filter to restrict the incoming light to a narrow waveband. If, for instance, we use a filter that only allows light in the blue part of the spectrum, we can measure a star's blue apparent magnitude, B. Similarly if we use a filter that approximates the eye's visual response which peaks in the yellow-green part of the spectrum we measure the magnitude *V* of a star.

Colour is defined as *the difference between the magnitude of a star in one filter and the magnitude of the same star in a different filter.*

The student is referred to project 3 for more details on the colours of stars.

4. Atmospheric extinction

Atmospheric extinction is the reduction of the intensity of radiation as a result of absorption and scattering by the Earth's atmosphere. About one sixth of the amount of perpendicularly incident light is extinguished in the visible domain.

Clearly, if the light has to pass through a larger path in the Earth's atmosphere, more light will be scattered/absorbed; hence one expects the least amount of absorption directly overhead (zenith), increasing as one looks down towards the horizon.

The ***airmass X*** is defined as the path length that the light from a celestial source must travel through the Earth's atmosphere to get to the observatory, relative to that for a source at the zenith (X=1 at Z=0), where Z is the zenith angle.

The magnitude outside the atmosphere, m_0, is related to the observed magnitude, m, by

$$m_0 = m + K_\lambda X$$

where K_λ *is the* ***extinction coefficient***. It can vary from night to night, so if you are interested in accurate photometry, you need to measure it on your night. Also remember that the extinction coefficient is wavelength dependent, so you need a separate number for each filter.

The extinction coefficient can be determined by making multiple observations of a star at different airmasses. Then you can obtain the values of K_λ and m_0 by fitting a straight line to the data (observed magnitudes versus airmass). Note that you need to sample a good range of airmasses to get good accuracy on the fit, and you must bracket the airmasses of all of your program objects.

Exercise 3: Calculate the extinction coefficients of the observatory from where your observations were made.

Follow these steps:

1. Calibration of CCD images. This involves bias subtraction and flat-field division

   Proceed as explained in Project 1

2. Obtain instrumental magnitudes.

   Proceed as explained in Project 1

3. Calculate atmospheric extinction

The extinction stars (standard stars) should be observed at airmasses corresponding to the range in airmass of the program objects (a range of not less than 0.5 magnitudes in extinction is suggested) so that a good airmass correction can be determined and applied to the data.

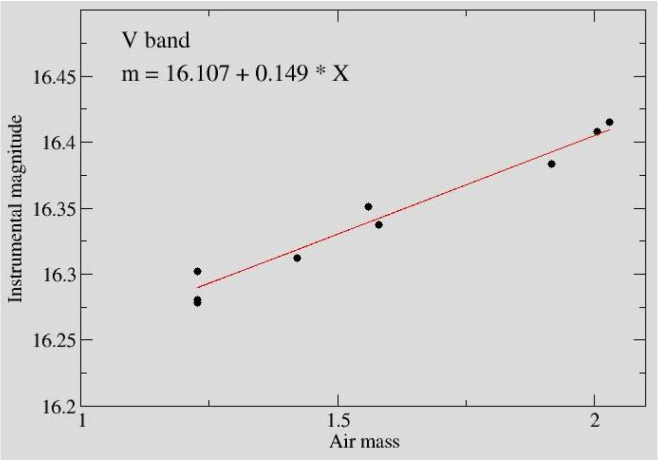
To derive the extinction coefficients plot the instrumental magnitudes obtained in step 2 as a function of the airmass. A straight line should provide a good fit to the data points since

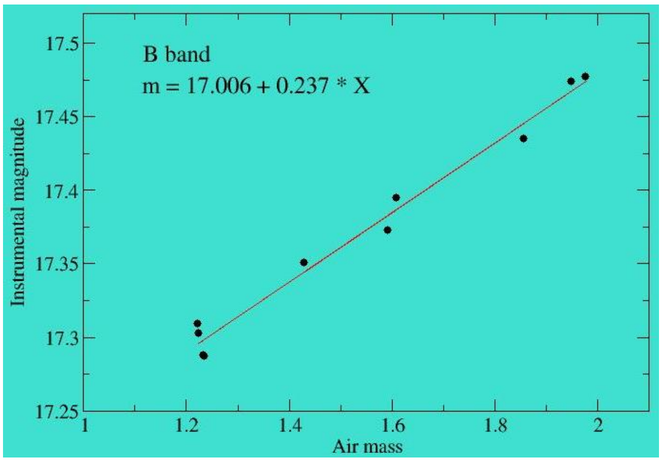
$$m_{ins} = m_0 + K * X$$

The slope will be the extinction coefficient, K, and intercept with the Y-axis the magnitude outside the atmosphere.

Repeat for each filter and for each standard with sufficient number of points. Look at the example below where the case of one standard is presented

B band		**V band**	
Air mass	Inst. mag.	Air mass	Inst. mag.
1.224	17.303	1.228	16.302
1.977	17.477	2.030	16.415
1.949	17.474	2.006	16.408
1.235	17.287	1.228	16.278
1.233	17.288	1.227	16.28
1.223	17.309	1.227	16.302
1.430	17.351	1.422	16.312
1.591	17.373	1.561	16.351
1.609	17.372	1.581	16.337
1.857	17.435	1.918	16.383





Thus, in the example above the extinction coefficients are K_B =0.237 and K_V =0.149.

Exercise 4: Calculate the magnitudes outside atmosphere, that is, corrected for the atmospheric extinction.

Once the extinction coefficient is known we obtain the extinction- corrected magnitudes for standard stars in each filter

$$m = m_{ins} - K * X$$

Here m_{ins} are the instrumental magnitudes (B_{ins}, V_{ins}), K the extinction coefficient obtained in step 3 (K_B, K_V) and m the corrected magnitudes (B_{obs},V_{obs}). Obtain also the colours corrected for extinction, (B-V)

B_{ins}	X_B	$B_{obs}=B_{ins}-K_B*X_B$	V_{ins}	X_V	$V_{obs}=V_{ins}-K_V*X_V$	$(B-V)_{obs}$
17.303	1.224	**17.013**	16.302	1.228	**16.119**	**0.894**
17.477	1.977	**17.008**	16.415	2.030	**16.112**	**0.896**
17.474	1.949	**17.012**	16.408	2.006	**16.109**	**0.903**
17.287	1.235	**16.994**	16.278	1.228	**16.095**	**0.899**
17.288	1.233	**16.996**	16.28	1.227	**16.097**	**0.899**
17.309	1.223	**17.019**	16.302	1.227	**16.119**	**0.900**
17.351	1.430	**17.012**	16.312	1.422	**16.100**	**0.912**
17.373	1.591	**16.996**	16.351	1.561	**16.118**	**0.878**
17.372	1.609	**16.991**	16.337	1.581	**16.101**	**0.889**
17.435	1.857	**16.995**	16.383	1.918	**16.097**	**0.898**

This has to be done for all your standard stars, irrespective of whether they were used for the extinction coefficient derivation.

5. Standard stars and transformation equations

Standard stars are required so that different observers are able to compare results with each other. The reason this is true is because every observational setup is likely to have different response functions, so the same stars will *not* be observed to have the same brightness (even relative brightness!) with each separate setup. Differences in response come from many factors: size and condition of the telescope optics, number and type of optics in the system, bandpass and quality of the filter, response function of the CCD, etc. To get around these problems, systems of standard stars have been set up so observers can calibrate their observations against the known brightness of the standard stars.

Transformation coefficients

$$M = m_0 + t\,(colour) + z$$

where capital letters are the magnitude on the standard system, z is the zero point, *t* is the transformation coefficient and m_0 is the magnitude outside the atmosphere obtained as explained above. The colour is generally parameterized by the difference between two magnitudes. The effective wavelengths of the two filters used to create the colour index should not differ too much from the wavelength of the filter being corrected; generally, one uses the bandpass being corrected as one of the wavelengths and an adjacent bandpass as the other. For example, when correcting V magnitudes, people usually use B-V for the color term.

Exercise 5: Obtain the transformation coefficient to the standard system.

The instrumental magnitudes have to be transformed to the standard system defined by a set of observed standard stars (these same standard stars can also be used as the extinction stars). These stars should be chosen prior to the observations so that their colors bracket those of the program objects (a good rule of thumb is to have at least a 0.5 magnitude range in the colors of the standards to determine reasonable calibrations). The transformation equations are the following

$$V = V_{obs} + C1 * (B-V) + C2$$

$$(B-V) = C3 * (B-V)_{obs} + C4$$

where V and (B-V) are the values we want to calculate and V_{obs} and $(B-V)_{obs}$ were calculated in exercise 4. In order to solve this equation we need to derive the values of the transformation coefficients C1, C2, C3 and C4. Since the magnitude and colours of the standard stars are known we can make use of these stars to derive the coefficients. For the standard stars we have

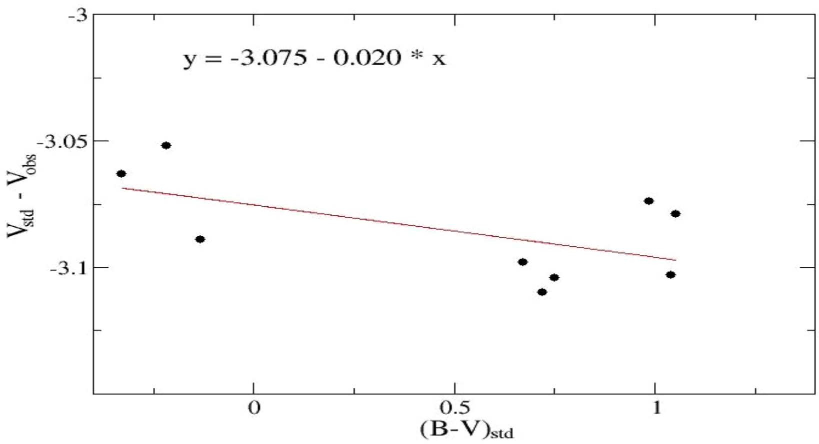
$$V_{std} = V_{obs} + C1 * (B\text{-}V)_{std} + C2$$

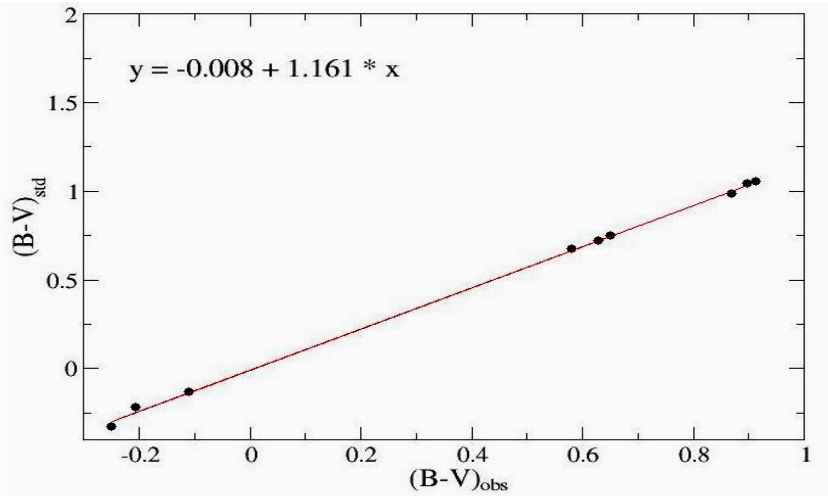
$$(B\text{-}V)_{std} = C3 * (B\text{-}V)_{obs} + C4$$

V_{std}, $(B\text{-}V)_{std}$, V_{obs} and $(B\text{-}V)_{obs}$ are all known quantities. The transformation coefficients can be obtained by fitting a straight line to V_{std}-V_{obs} vs $(B\text{-}V)_{std}$ and $(B\text{-}V)_{std}$ vs $(B\text{-}V)_{obs}$.

The standard magnitudes and colours are obtained from a catalogue of standard stars. One such catalogue can be found in Landolt (1992, AJ, 104, 340). The values for 9 standard stars from Landolt's catalogue are shown below. Here the average of the instrumental magnitude V_{obs} and colour $(B\text{-}V)_{obs}$ was obtained first (note that you may have several values of V_{obs} and $(B\text{-}V)_{obs}$ for different airmass).

V_{obs}	$(B\text{-}V)_{obs}$	V_{std}	$(B\text{-}V)_{std}$	V_{std}-V_{obs}
16.107	0.897	13.004	1.040	-3.103
17.275	0.912	14.196	1.052	-3.079
14.811	0.869	11.737	0.987	-3.074
17.849	-0.109	14.760	-0.132	-3.089
19.168	-0.249	16.105	-0.329	-3.063
17.176	-0.205	14.124	-0.217	-3.052
17.276	0.580	14.178	0.673	-3.098
15.810	0.650	12.706	0.749	-3.104
18.219	0.629	15.109	0.721	-3.110





Thus,

C1=-0.020	C3=1.161
C2=-3.075	C4=-0.008

Exercise 6: Obtain the absolute magnitude and colour of your target star.

If the instrumental magnitudes of the target object are

B_{ins}=18.555 at X_B=1.025, V_{ins}=17.559 at X_V=1.029

then

B_{obs}=18.312, V_{obs}=17.406

and

(B-V)=1.161*(18.312-17.406)-0.008=1.044

V=17.406-0.020*1.044-3.075=14.31

B=V+(B-V)=14.31+1.044=15.35

Exercise 7: Estimate the uncertainty of the previous results.

A measure of the uncertainty in the magnitudes can be derived by calculating the standard deviation between the standard and the calculated values of the standard stars.

Vobs	(B-V)obs	Vstd	(B-V)std	Vstd-Vobs	V-Vstd	(B-V)-(B-V)std
16.107	0.897	13.004	1.040	-3.103	0.009	-0.006
17.275	0.912	14.196	1.052	-3.079	-0.015	-0.001
14.811	0.869	11.737	0.987	-3.074	-0.020	0.015
17.849	-0.109	14.760	-0.132	-3.089	-0.004	-0.003
19.168	-0.249	16.105	-0.329	-3.063	-0.031	0.032
17.176	-0.205	14.124	-0.217	-3.052	-0.042	-0.029
17.276	0.580	14.178	0.673	-3.098	0.004	-0.008
15.810	0.650	12.706	0.749	-3.104	0.011	-0.002
18.219	0.629	15.109	0.721	-3.110	0.016	0.001
Standard deviation →					**0.020**	**0.017**

$$err(B) = \sqrt{err(V)^2 + err(B-V)^2 = 0.020^2 + 0.017^2} = 0.03$$

Thus, the final results for the target object are

B=15.35±0.03

V=14.31±0.02

(B-V)=1.044±0.17

6. Interstellar extinction & distance estimation

If the apparent magnitude of a star is known and there is some way to deduce the absolute magnitude, then a number known as the **distance modulus, m-M** can be computed. This distance modulus can be converted into an actual distance through

$$m-M=-5+5\log_{10}(d)$$

Although we think of interstellar space as a vacuum, it is in fact filled with tenuous gas and dust. Like a smoke-filled room, the gas and dust along the line of sight to a star dim the starlight by absorbing and scattering the light. This effect is called ***interstellar extinction***. If we do not account for this extinction, we will overestimate the distance to the star.

Extinction is stronger at shorter wavelengths, as shorter wavelengths interact more strongly with dust particles. Red light passes through gas and dust more easily than blue light. The more gas and dust between you and the source, the stronger the reddening. You observe this effect daily! When the Sun and Moon are near the horizon, you are viewing them through more atmosphere than when they are overhead. That is why the Sun and Moon look reddish when they rise and set. The reddening of starlight due to the interstellar extinction is known as ***interstellar reddening***. Astronomers often used the terms extinction and reddening interchangeably.

The extinction or reddening to an object is usually given in magnitudes, and denoted by an upper case **A**. Since extinction is a function of wavelength, a subscript specifies the wavelength for the stated value. A star whose light is dimmed by 1.2 magnitudes when viewed through a V filter would have an extinction of $A_V = 1.2$.

How do we correct the equation for distance when accounting for extinction?
Without extinction,

$$d = 10^{0.2\,(m - M + 5)}$$

If you want to account for extinction just remember that lower magnitudes are brighter, so you want to subtract A_V from the apparent magnitude. The revised equation is thus

$$d = 10^{0.2\,(m - M + 5 - A_V)}$$

where d is the distance in parsecs. A_V can be determined from the observed and expected colour index B-V as

$$A_V = 3 \times E(B\text{-}V) = 3 \times [(B\text{-}V)_{obs} - (B\text{-}V)_0]$$

where $(B\text{-}V)_{obs}$ is the observed colour index and $(B\text{-}V)_0$ is the expected colour index for the particular object that we are observing. The values of $(B\text{-}V)_0$ can be found in books on Astronomy. We give below a table relating the spectral type of the star and the $(B\text{-}V)_0$.

Exercise 8: Estimate the distance of the target star.

[This exercise can only be performed if the spectral type (or intrinsic colour) of your target object is known]

1. Find out the intrinsic colour of your target object. You need to know its spectral type. You can find the spectral type using the SIMBAD database (http://simbad.u-strasbg.fr/Simbad). Then using the calibrations given in the bibliography (see, for example, Wegner 1994, MNRAS 270, 229; Jonhson 1966, ARA&A 4, 193) you can find the intrinsic colour of the star, $(B\text{-}V)_0$.

   The spectral type of the object considered above is B0V.

   The intrinsic colour for such a star is $(B\text{-}V)_0=-0.27$.

2. Obtain the colour excess $E(B\text{-}V)=(B\text{-}V)-(B\text{-}V)_0$, where (B-V) is the value obtain in the previous exercise and derive the extinction in the V band, $A_V=3.1*E(B\text{-}V)$.

   $E(B\text{-}V)=(B\text{-}V)-(B\text{-}V)_0 = 1.044+0.27 = 1.314$

   $A_V=3.1*E(B\text{-}V) = 3.1*1.314 = 4.07$

3. Find out the absolute magnitude, M_V, of your object (see e.g. Wegner 2000, 319, 771, Greiner et al. 1985, 145, 331; Mikami & Heck, 1982, PASJ, 32, 529)

   The absolute magnitude of a B0V star is $M_V=-4.2$

4. Calculate the distance (in parsecs) of your object using the distance-modulus equation

$$d = 10^{0.2\,(V - M_V + 5 - A_V)}$$

$d = 10^{0.2\,(V - M_V + 5 - A_V)} = 10^{0.2\,(14.31+4.2+5-4.07)}$ ~ 7700 pc ~ 7.7 kpc.